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III-V ON SILICON MICRO PHOTONIC CIRCUITS FOR FREQUENCY DOWNCOMVERSION OF RF SIGNALS

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\begin{equation}
G_{IF}(\omega) = \frac{R_{i}}{R_{0}}R_{L}^{2}G_{FE}G_{IF}|H_{RF}|^{2}|H_{IF}|^{2}.
\end{equation}

in which \(R_{i}, R_{0}\) and \(R_{L}\) are the load impedances (all assumed 50\,\Omega), \(G_{FE}\) and \(G_{IF}\) are the front-end and IF amplifier gains, \(|H_{RF}|^{2}\) and \(|H_{IF}|^{2}\) represents the insertion loss of the input image rejection filter and IF output filter respectively. The second part of the equation comprises all parameters of the photonic building blocks; the photodetector responsivity \(R\), the insertion loss of the modulator \(A\), the \(V_{pi}\) of the modulator, the S21 parameter of the modulator (at 30\,GHz in our specific application) and that of the photodetector (at 1.5\,GHz in our specific application). \(P_{0}\) is the average output power from the pulsed laser source. The last term describes a conversion penalty due to the finite duration of the pulses, corresponding to a power reduction of the Nth RF harmonic of the pulse train envelope compared to the fundamental one.

III. MICRO PHOTONIC BUILDING BLOCKS

A. III-V on silicon photonic platform
The components required for the electro-photonic frequency converter can all be implemented on a III-V semiconductor platform (InP/InGaAsP). However, better performance can be expected when integrating such III-V devices on a passive silicon photonic platform that provides low-loss passive waveguide circuits and high-resolution lithography for the definition of e.g. grating structures. The integration of III-V material onto such a platform is done through adhesive die-to-wafer bonding in which a III-V die, comprising the III-V epitaxial layer stack is bonded epi-side down onto the silicon waveguide circuit using DVS-BCB as the transparent polymer bonding agent. After bonding, the III-V substrate is removed and the III-V component is fabricated lithographically aligned to the underlying silicon photonic circuit [2]. The optical coupling between the 400nm thick silicon device layer and III-V layer (and vice versa) is done through an adiabatic taper structure [3]. In this project 3 basic components are developed: a hybridly modelocked laser, an electroabsorption modulator and an IF-band photodetector, which we will detail in the following subsections.

B. III-V on silicon modelocked laser

Semiconductor mode-locked lasers generating short (~ps) optical pulses at GHz repetition rates are of interest in a range of applications due to their compact size, low power consumption and ruggedness. In the electrophotonic frequency converter application low phase noise performance is of paramount importance. Fundamentally, the noise performance is determined by the spontaneous emission generated in the amplifier section of the mode-locked laser. Therefore, limiting the length of the semiconductor optical amplifier and realizing a low-loss optical cavity, consisting for a large part out of passive waveguides is key. This can be realized on a III-V semiconductor platform by active-passive integration. However, the passive waveguide losses on a III-V semiconductor platform are typically in the 2-3dB/cm range, thereby inducing substantial loss when long cavities (low repetition rates) are required. Replacing the III-V passive waveguide circuit by a silicon photonic integrated circuit can reduce the cavity loss, due to the well-developed CMOS fabrication technology, used to realize such waveguides. Moreover, at telecom wavelengths also the two-photon absorption losses are substantially lower in silicon compared to InP-based waveguides, thereby creating less excess loss due to the high peak power nature of the optical pulses traveling in the mode-locked laser cavity.

Two types of modelocked lasers were compared: a linear cavity geometry with a central saturable absorber to work in colliding pulse mode and a ring based geometry, also working in colliding pulse mode, but where both pulse trains couple to a separate output, as shown in Fig. 1. The longitudinal cross-section of the III-V semiconductor optical amplifier and saturable absorber is shown in Fig. 2. A III-V/Si taper structure is used to couple the III-V amplifier sections to the silicon waveguide circuit. Since in the passive modelocking regime the phase noise specs for the EPFC could not be reached, hybrid modelocking was required using an external LO. In this approach the residual phase noise from the modelocked laser was very low. Depending on the driving conditions, 2 to 5ps wide optical pulses were generated and the average output power of the modelocked laser reached 6dBm. The output spectra of both the linear cavity and ring-based cavity over a wide frequency range are shown in Fig. 3 (a) and (b) (50 GHz and 25 GHz) respectively. From these wide range spectra stronger spurious signals can be seen in the linear cavity geometry. Therefore, a linear cavity geometry will be used in the final EPFC. The generated RF comb is relatively flat, due to the short pulse duration.

Fig. 1. Modelocked laser configurations: linear cavity based structure (a) and ring-based cavity (b)
As the signal that is to be downconverted is in the 30GHz range, the optical modulator should support such bandwidth. This was realized by implementing a traveling wave electro-absorption modulator integrated on a silicon photonic platform. The cross-section of the III-V on silicon electro-absorption modulator is shown in Fig. 4. The traveling wave structure is terminated by a 50Ω impedance. The DC response of the fabricated electroabsorption modulator is shown in Fig. 5(a), while the normalized $|S_{21}|^2$ response as a function of frequency is shown in Fig. 5(b) at -1.2V bias. From the DC response curves an equivalent $V_{pi}$ of 8V can be deduced. The reason for such a high $V_{pi}$ is not yet understood. The epitaxial layer structure is different from that of the modelocked laser. This can be accommodated by double die-to-wafer bonding and collective processing of the modelocked laser and EAM.
Fig. 5 Electroabsorption modulator characteristics: (a) DC response; (b) RF response.

D. III-V on silicon photodetector

The IF-band photodetector is implemented in the same layer stack as the laser, allowing straightforward co-integration of both opto-electronic components. A responsivity of 0.8A/W and a bandwidth far exceeding 2 GHz at 1V reverse bias was obtained.

IV. CONCLUSIONS

In this paper we present the development of the building blocks required to implement an electro-photonic frequency converter based on micro-photonics. A low phase noise modelocked laser, high bandwidth electroabsorption modulator and high responsivity photodetector is demonstrated on a III-V on silicon platform. All building blocks can be co-integrated to realize an ultra-compact Ka to L-band downconverter. A different topology can also be considered, where the optical LO signal is centrally generated and distributed to an array of electrophotonic mixers.

REFERENCES

